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Toward Less Conservative Flotation Criteria for Lightweight Cables And Pipelines.

Tommaso Bizzotto[1], Michael John Brown[1], Toby Powell[2], Andrew John Brennan[1], Howard Chandler[3]

[1]School of Science & Engineering,
University of Dundee,
Dundee,
United Kingdom

[2]Subsea 7,
Aberdeen,
United Kingdom

[3]School of Engineering,
University of Aberdeen,
Aberdeen,
United Kingdom

ABSTRACT
This paper aims to give a new perspective on possible criteria for the pipeline and cable flotation phenomenon. Laboratory flotation and pull-out tests have been conducted in high moisture content kaolin clay using a model pipeline or cable analogue of 63mm diameter installed at different embedment depths. Uncertainty over the definition of "flotation" has led to comparison of data from previous studies and those obtained from the pull-out tests described herein. Different definitions of flotation may lead to a significant increase in the magnitude of available resistance used in design which can directly affect the commercial choices made for commercial pipelines and cables (e.g. coating type and thickness and minimum burial depth).

KEY WORDS: flotation, pull-out, kaolin clay, Atterberg limits, liquidity index, pipeline, cable, lightweight, specific gravity.

INTRODUCTION

The increased presence of offshore activities poses the problem on how to achieve fast, safe and economically convenient connection between offshore and onshore facilities with the use of pipelines and cables. In regions where fishing and ship anchoring operations are present, the trenching and backfilling of pipelines and cables is required to provide mechanical protection. In cold regions, the backfilling is necessary to achieve the proper thermal insulation (Finch and Machin 2001) for pipelines that transport oil. Optimised pipeline and cable trenching and backfilling increases the necessity for better understanding of the soil-pipe interaction, especially where there are uncertainties with respect to the short and long term properties of backfilled soil which are highly dependent on the installation technique (Cathie, et al. 2005). To reduce fabrication cost and improve handling there is an obvious requirement to employ lighter materials with the requirement that the mechanical and thermal properties are met. For pipelines the insulation is typically provided by a scheme of multilayered coatings incorporating for example a layer of polymer foam (i.e. polypropylene, polyvinyl chloride, polyurethane) (Palmer and King 2008). If resistance to hydrostatic pressure is required, to avoid the foam crushing, a pipe in pipe scheme may be adopted. This scheme is designed such that the external pipe absorbs the mechanical and hydrostatics forces and the inner pipe carries the fluid. Both techniques of providing thermal insulation rely on an increased diameter of the pipe with much lighter materials, this leads to an overall increase in cross-sectional area but with a relatively lower increase in weight due to lower unit weight of the insulating material. The unbalanced growth in pipe volume with respect to self-weight lead to a reduction of the equivalent unit weight of the circular section.
An additional way to reduce the economic cost for the pipeline handling and mechanical protection is to adopt a fast and less demanding trenching technique such as the post-lay trenching technique (Finch and Machin 2001). This technique consists of fluidizing the soil beneath the pipeline/cable with highly pressurized water injected by an ROV (remote operated vehicle). At this point the pipe sinks into the fluidized soil and comes to rest at the bottom of the trench (Powell, et al. 2002). With time the fluidized soil slurry above the pipeline or cable starts to reconsolidate under its own self weight, increasing its unit weight, strength and resulting resistance to pipe/cable flotation or operational uplift. Jet trenchers are substantially easier to handle and deploy compared with the bigger much heavier trenching and backfilling ploughs. With this process jet trenchers can form the trench and backfill the pipeline in one pass.(Maconochie, et al. 2015).
The soil after the jet trenching process in fine grained soils is thought to be lumpy (Brennan, et al. 2017) and not completely disaggregated (White and Cathie 2011). For example, Nobel (2013) recognized that the structure of soil left by jetting is dependent upon the type of jet used in fine grained soils. Machin and Allan (2010) state that a complete fluidized fine grained soil is possible especially in soft clays and loose silts. This may lead to possible flotation issue with lightweight pipelines and cables where for economic reasons the weight of the pipeline is optimized for handling, settlement through the slurry/blocks in the trench and to maintain position and stability in the short term as the slurry regains strength and later under operational conditions. Currently guidance on avoiding flotation is limited to anecdotal adoption of values of pipeline weight designed to achieve a specific gravity (SG) of 1.7-1.8 but the origins of such recommendations are unclear. Powell et al. (2002) propose a value of SG from 1.5 to 1.7 as a minimum criteria for flotation based upon flotation tests, but without reporting the dataset to be compared with our results or a flotation criterion. Optimization of this SG based design approach requires accurate knowledge of how the slurry/pipeline cable interact under different conditions and how flotation is actually defined in terms of movement or serviceability of the pipeline or cable.

FLOTATION

Flotation in water and more generally in Newtonian fluids is well understood and obeys Archimedes' principle. It has been proven by Ghazzaly, et al. (1975) and Ghazzaly and Lim (1975) that the same force equilibrium as Archimedes can be adapted for fluidized soils using the unit weight of the fluidized soil (γ_s) instead of water (γ_w), with an additional resisting force applied by the soil as a reaction to the floating vertical upward movement of the pipe (Fig. 1)

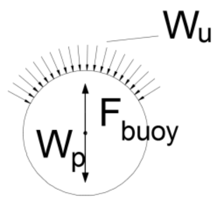

Fig. 1 Flotation equilibrium representation W_p=weight of the pipe/cable per unit length, F_{buoy}=buoyancy force per unit length, W_u= resistance provided by the mobilized soil mechanism per unit length.

The same equilibrium can be expressed in equation (1):

$$(W_u + \mathrm{W}_p - \mathrm{F_{buoy}}) \cdot \mathrm{L} = 0 \;\; \rightarrow$$
$$\rightarrow \;\; W_u + \gamma_\mathrm{p} \cdot \frac{\pi \mathrm{D}^2}{4} - \gamma_\mathrm{s} \frac{\pi \mathrm{D}^2}{4} = 0 \qquad (1)$$

Where W_u is the resistance of the fluidized soil per unit length, W_p is the weight of the pipe per unit length, $\mathrm{F_{buoy}}$ is the weight of the volume of fluidized soil replaced by the pipe per unit length, $\frac{\pi D^2}{4}$ is the cross sectional area of the pipe or cable and L the length of the pipe.
A simple way to represent and visualize the flotation potential is to use the equivalent specific gravity of the pipeline, the specific gravity (SG) is the ratio of material density to reference material, in this case seawater. Seawater has a density in open ocean at the surface ~1021 [kg/m^3] (Kennish 2000), that is although controlled by salinity, temperature and pressure. If an object that has an SG>1 is immersed in water it will sink, on the contrary if the object has an SG<1 it will float. If the object is immersed in fluidized soil the heavier unit weight of the soil will allow heavier objects to float. The high unit weight of the fluidized soil increases the buoyancy force and is the main factor that contributes to flotation issues in trenches formed with the jet trenching technique, although the contribution of the soil resistance mitigates the flotation effect to some degree.

MODEL TESTING EQUIPMENT AND PROCEDURES

For this study two types of test were designed, a pull-out test at constant low extraction velocity (0.2mm/s) and a flotation test similar to that undertaken by Ghazzaly, et al. (1975). Both types of test were carried out on a fluidized soil bed previously mixed at the moisture content of 100% and then increased to the required moisture content for the test. The flotation equipment was also manufactured in a similar manner to that presented by Ghazzaly, et al. (1975). The model pipe/cable and the soil container (Fig. 2) were manufactured to have a small gap between the end of the pipe and the side wall, to prevent pipe wall friction and to allow a plain strain representation of the resisting mechanism in the fluidized soil. The overall dimensions of the container were 650 mm x 400 mm x 650 mm, and the pipe measured 398 mm in length and 63 mm in diameter. When the pipe was embedded in the soil, connection to the loading/measurement system was provided via two steel tubes, 6 mm in diameter. The steel tubes allow reduction or increase of the pipe weight through the addition of water as well as measurement of the upward displacement of the pipe via an LVDT and mechanical connection for the pull-out tests. Ghazzaly, et al. (1975), Ghazzaly and Lim (1975) and Endley, et al. (2009) have previously conducted tests on pipeline flotation in soil slurries of varying strength/moisture content, unfortunately though the criteria for flotation determination was not outlined (i.e. the upward displacement which was considered the point where flotation had occurred) and the methods of sample formation and pipeline installation were not clearly explained with different testing techniques adopted. This makes interpretation, reproduction and comparison with theses previous studies difficult. For flotation tests Ghazzaly, et al. (1975), Ghazzaly and Lim (1975) started with a stable pipe and reduced the unit weight of the pipe until flotation occurred. Endley, et al. (2009) started with a floating pipe and increased the weight of the pipe until flotation ceased. The tests reported herein adopted the first methodology, with the additional steps, that the pipe started above the soil and was pushed-in through a layer of water and then through the

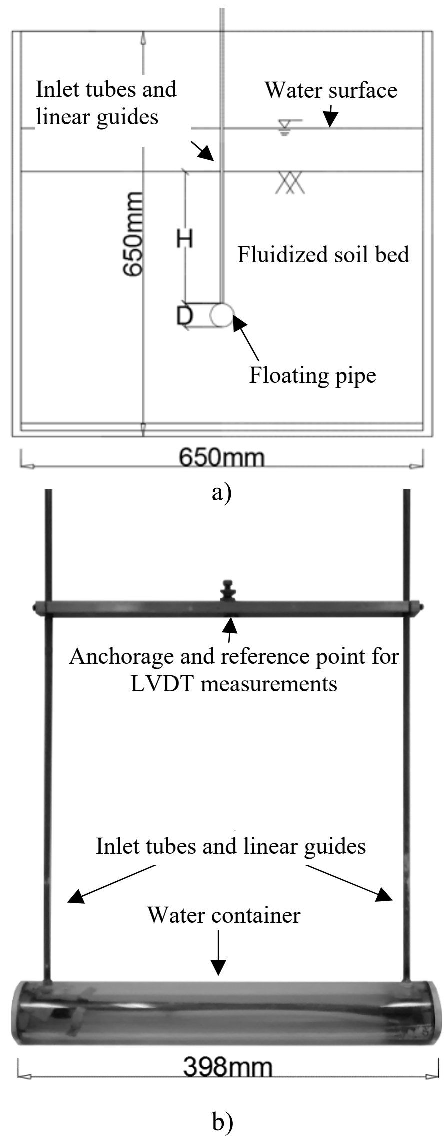

Fig. 2 Flotation apparatus: a) side view schematic of the container and pipe; b) front view image of the pipe.

soil (prior to the flotation test). At the correct depth the insertion was stopped and the pipe locked in place. Initially the unit weight of the pipe was set to be heavier than the unit weight of the slurry. The weight of the pipe was then decreased by removing water from the inside of the pipe, via the inlet tubes, and a lower unit weight was achieved. With the pipe at the right weight it was released and the movement was recorded. The pipe was left to achieve an equilibrium state, where the net buoyancy force and the soil resistance were equal. The equilibrium state was set to correspond to a maximum displacement of the 2% of the diameter in 1hr, which for this pipe means a velocity of 1.26 mm/hour (3.5·10-4mm/s). Once the pipe reached the limiting velocity it was returned to the starting depth, locked in position and the weight reduced, to repeat the test again. The sequence of tests stopped when the unit weight of the pipe could not be reduced any further. At this point the soil and the water directly above the pipe were removed and the soil remixed again for testing at another depth. The depth tested were H/D=2 and 1.5, with D and H represented in Fig. 2a. After the flotation tests were completed at the various depths, the soil was remixed again and a pull-out type test was performed at each different depth, force-displacement relationships were recorded. Each pull-out and flotation type test was preceded by an insertion stage which involved penetrating the model pipe through the water and soil layers at a constant velocity of 0.6mm/s. This was meant to produce a less uniform soil above the pipe and allow some limited simulation of the installation process. Figure 3 shows the soil above the pipe after the process where water lenses can be clearly seen.

Fig. 3 typical texture of soil post insertion soil bed at moisture content w=139%.

The soil utilized for these tests was Speswhite kaolin clay, which Atterberg limits are reported in *Table 1* with a comparison of soils utilized in other studies. Soil number 3 of Endley, et al. (2009) has not been included in the comparison because of the lack of the liquid limit (LL) reported in their paper. The soil for the tests carried out in this study was initially mixed at a moisture content (w) of 100%, then a percentage of water enough to reach the new testing moisture content was added. The slurry was then thoroughly remixed for the tests at the required specific moisture content. Table 2 reports the testing moisture content range (w) for the pull-out and flotation tests.

Table 1 soils properties comparison

Study	Soil type	Liquid limit (LL)	Plastic limit (PL)	Grain specific gravity (Gs)
Ghazzaly, et al. (1975) & Ghazzaly and Lim (1975)	Soil 1	46	23	2.69
	Soil 2	76	21	2.83
Endley, et al. (2009)	Soil 1	49	14	-
	Soil 2	85	26	-
Present study	Kaolin clay	65	32	2.55

FLOTATION AND PULL-OUT TESTS

For each flotation test, the weight of the water withdrawn from inside the pipe was recorded and then the pipe was released. The variation between each flotation test (conducted in the same soil bed, prepared at a specific moisture content w%) was the reduced unit weight of the pipe. Given that the unit weight of the soil (γ_S) and the diameter of the pipe were constant, the different flotation loads were directly dependent on the weight of the pipe. During the flotation test the weight of the pipe was constant. The displacement was recorded with time, for each test at different unit weight of the pipe. Fig. 4 shows the data recorded during six flotation tests at a moisture content of w=201%, the weight of the pipe is kept constant during each flotation test. It can be seen that that at every floating unit weight (or specific gravity) of the pipe there is a large initial displacement at the beginning of the test, when the pipe was released, but then each test tended to an equilibrium stage where the displacement and the velocity of the pipe reduces significantly. The movement of the pipe stopped due to reaching equilibrium between the soil resistance mobilized by the movement of the pipe and the buoyancy force. This equilibrium is expressed in equation (1). The other type of tests undertaken as part of this study were pull-out. With these two methodologies of test, flotation and pull-out, it was possible to compare force-displacement relationships and it was found that very similar force-displacement relationships were obtained for the two types of tests (Fig. 5). For this reason, further comparison is based upon the results of pull-out testing only rather than flotation testing due to ease of testing and the utility of continuous load-deflection curves.

Table 2 investigation moisture content, liquidity index range

Study	Moisture content (w) [%]	Liquidity index range (LI)
Ghazzaly, et al. (1975) & Ghazzaly and Lim (1975)	74%-106%	2.2-3.6
	80%-120%	1.1-1.18
Endley, et al. (2009)	64%-110%	1.42-2.74
	136%-209%	1.86-3.10
Present study	239%-228%	3.23-5.95

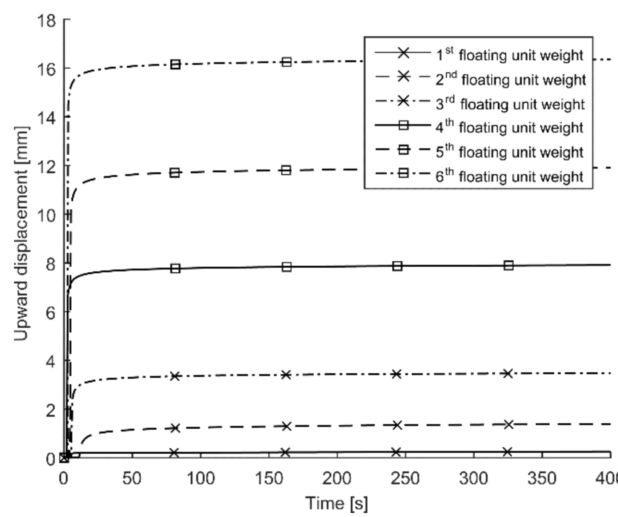

Fig. 4 upward pipe displacement at different unit weight (w=214%). The "1st floating unit weight" represent the heaviest pipe unit weight, the "6th floating unit weight" represent the lightest pipe unit weight. (Unit weights have been omitted for confidentiality reasons)

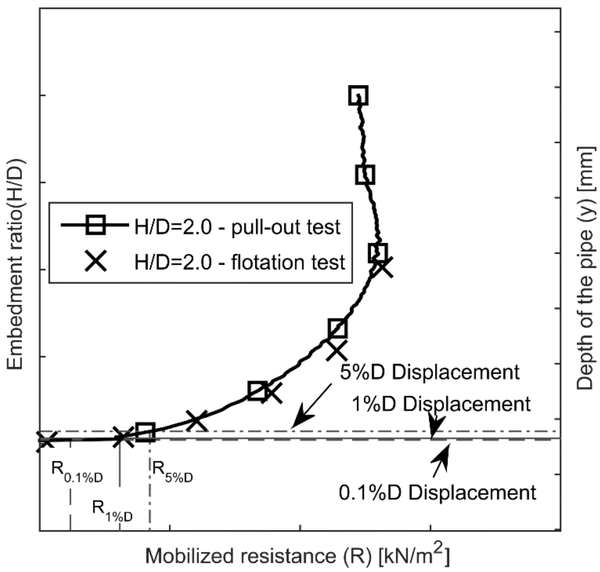

Fig. 5 comparison of pull-out and flotation tests force-displacement relationship at moisture content w=217%, H/D=2. (Values have been omitted for confidentiality reasons)

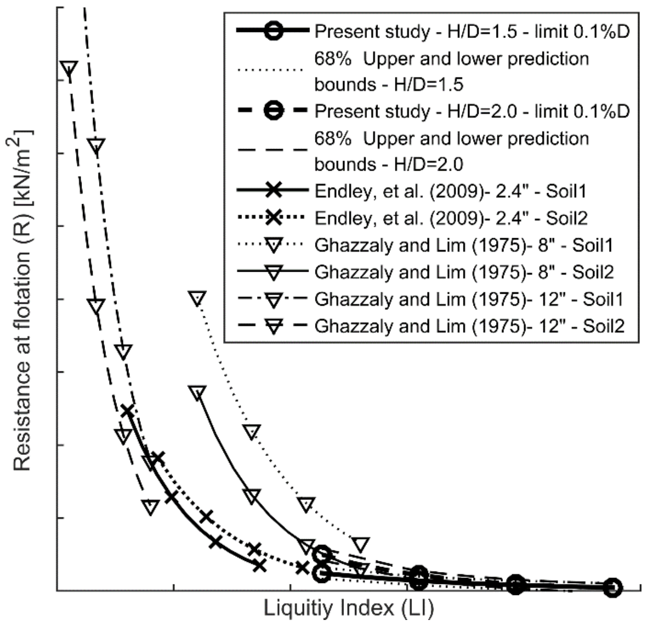

Fig. 6 Flotation criterion interpolation comparison from Ghazzaly and Lim (1975) and Endley, et al. (2009) and first fit of the present study interpolated data at 0.1%D displacement. (Values have been omitted for confidentiality reasons)

DATA COMPARISON WITH PREVIOUS STUDIES

Although Ghazzaly and Lim (1975) and Endley, et al. (2009) used different approaches to determine flotation and three different pipe diameters, their results were compared in this study. This allows comparison of the flotation resistance against the soil's liquidity index (LI) and to verify if this is a viable method for comparison of results from different tests and soil types. The diameters and the embedment ratios tested are reported in Table 3. The data concerning loads and resistance in the graphs reported in this paper have been omitted for confidentiality reasons.

Table 3 pipe diameters and embedment ratios comparison

	Diameter (D)	Embedment ratio (H/D)
Ghazzaly, et al. (1975) & Ghazzaly and Lim (1975)	203.2mm (8") 304.8mm (12")	1.5
Endley, et al. (2009)	60.96mm (2.4")	1.5-2
Present study	63mm	1.5 and 2

The way comparison has been approached was to assume that the resistance over unit length of the pipe/cable exerted by the soil was function of the undrained soil shear strength (S_u) and proportional to both a bearing capacity coefficient (N_C) and the diameter of the pipe, as expressed in equation (2). This kind of approach has already been used by Ghazzaly, et al. (1975), and is a common way to treat pipeline upheaval buckling resistance in fine grained material after the plasticity analysis of Randolph and Houlsby (1984).

$$W_u = N_C \cdot S_u \cdot D \qquad \left[\frac{\mathrm{kPa}}{\mathrm{m}}\right] \tag{2}$$

including equation (2) in equation (1) has been possible to compare R as a pressure:

$$R = (\gamma_s - \gamma_p)\frac{\pi D}{4} = N_C \cdot S_u \qquad \left[\frac{\mathrm{kPa}}{\mathrm{m^2}}\right] \tag{3}$$

With the uncertainty in determining the undrained shear strength of soil at very high moisture contents the comparison has been made based on the resistance (R), as a function of the product ($N_C \cdot S_u$). Fig. 6 presents the values of the resistance at flotation (R). The values of R from the studies cited above have been interpolated and represented against the respective liquidity index (LI). Fig. 6 also shows the data interpolated from pull-out tests at the displacement that best matches the resistance at flotation (R) from Ghazzaly and Lim (1975) and the 2.4" pipe from Endley, et al. (2009). The best fit is given by a displacement that is equal to 0.1% the diameter (D), that correspond to 0.063mm in the case of the pipe used here. *Fig. 6* shows that whatever criteria was used to define flotation in the previous studies there assumptions were generally consistent.

CRITERION COMPARISON

Although it has been shown in Fig 6 that a good comparison of the work undertaken here with previous studies can be achieved based upon a flotation criteria of 0.1%D (upward movement), it can also be seen that the strength of soil here is much lower than previous studies (or higher LI). It is apparent in Fig 5, though, that there is much more potential resistance to pipeline flotation available if limited upward movement can be allowed. To highlight this Fig 6 is replotted with the resistance (R) determined at 1%D and 5%D against the data provided from the previous studies in Fig. 7~8. A substantial increase in the resistance to the flotation is provided by the additional allowance of upward displacement distance, this means that the resistance, once the pipe moves upward increases due to more developed uplift mechanism (greater resistance to uplift is mobilized, Fig. 5). In Fig. 7~8 it is clear that much greater uplift resistance can then be achieved in soils at higher moisture contents (lower strengths) than in previous studies if the flotation criteria can be relaxed. Fig. 9 shows the ratio of resistance at the increased displacement level over that at 0.1%D (referred to as the normalized flotation resistance) and how the increase is slightly nonlinear over the range of liquidity index investigated. It is clearly shown that there is a significant increase in the resistance (between 300 and 400 times) at H/D=2, with a relatively small change in flotation or displacement criteria from 0.1%D to 1%D. This increases further when displacement up to 5%D are allowed (500 and 1000 times). This highlights that stating a single resistance to flotation (i.e. a single value of non-floating SG) may be misleading and that significantly greater resistance to flotation can be achieved in weaker soils (than previously studied) if mobilization of flotation resistance is considered appropriately.

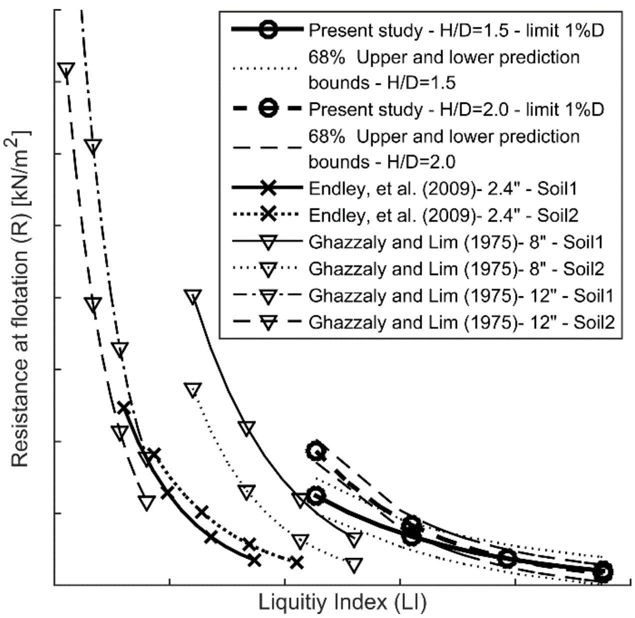

Fig. 7 Flotation criterion interpolation comparison from Ghazzaly and Lim (1975) and Endley, et al. (2009) and first fit of the present study interpolated data to the previous studies at 1.0%D displacement. (Values have been omitted for confidentiality reasons)

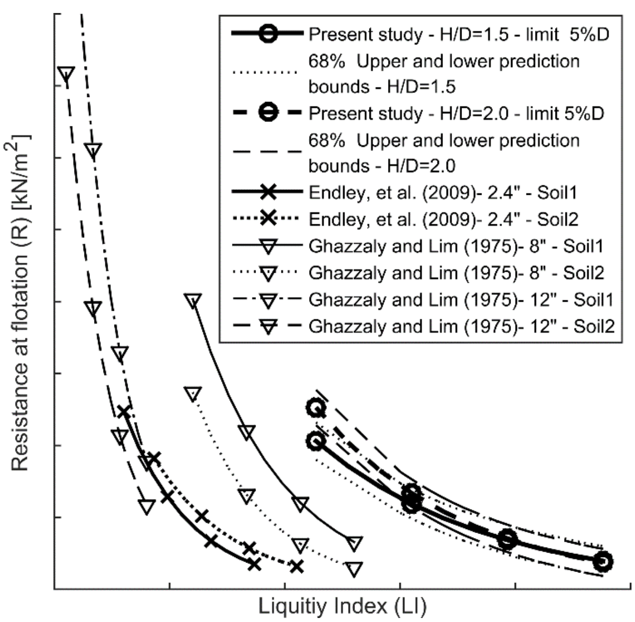

Fig. 8 Flotation criterion interpolation comparison from Ghazzaly and Lim (1975) and Endley, et al. (2009) and first fit of the present study interpolated data to the previous studies at 5.0%D displacement. (Values have been omitted for confidentiality reasons)

CONCLUSIONS

It has been shown in this paper how resistance to floatation of a pipeline or cable at flotation can be represented without the influence of the soil plasticity or pipe dimension. Although different equilibriums are possible due to the specific gravity of the embedded pipe, the available upward deflection of the cable/pipe must be properly assessed in the light of the future service life of the infrastructure. Localized movements can induce out of straightness imperfections, which could lead to weaker points when it comes to resist to upheaval buckling. The possibility to employ a pipe or cable with reduced specific gravity (SG) must be carefully evaluated; there were no evidences at date that less conservatives approaches where proposed in the recent years, latest published work on flotations topic at authors knowledge is Powell, et al. (2002), in which is stated that the risk increase with an SG over 1.7.

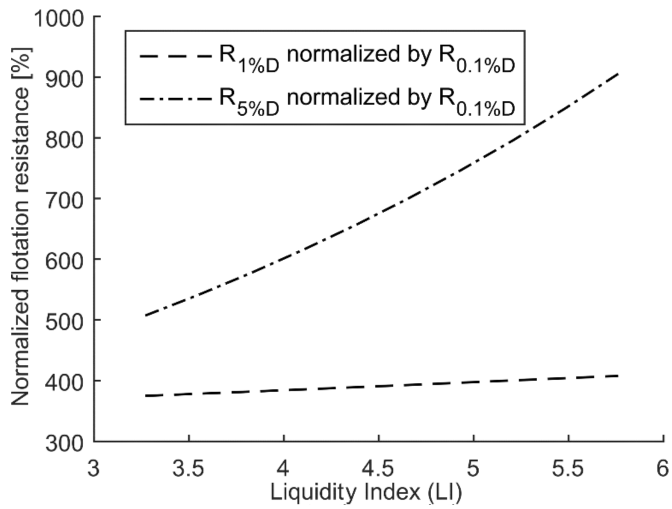

Fig. 9 flotation criteria improvement comparison as a function of liquidity index for H/D=2

The data acquired for this study extend the dataset of liquidity index investigated for flotation and investigate as well the influence of depth of embedment as a parameter that play a role also in pipe flotation.

The overlapping of results from different soils, pipe diameters and publications give confidence on the modelling of flotation resistance (R) as an independent variable from the diameter (D) of the floating object.

This paper presents the results of a model study where a model pipeline that has the facility to vary its weight (SG) has been used to investigate the effect of soil properties and embedment depth on the tendency for a cable or pipeline to float during or after installation by jetting. This study is designed to allow more accurate design of the minimum pipeline or cable weight to avoid flotation resulting in a pipeline or cable being out of specification. The study is also designed to improve on previous studies where there is little published detail on the specifics of the model testing undertaken and the criteria used for flotation. The study has shown that flotation testing in very high moisture content (low strength soils) can be represented by simple pipe/cable pull out testing. Comparison of the data here would suggest that previous studies may have used a very strict, and potentially conservative criterion for definition of flotation where upward displacements of the pipes were limited to 0.1% of the pipe diameter. The results here show that if greater upward displacements of pipelines and cables can be tolerated then there is potential to mobilize greater soil resistance even in very low strength soils resulting in the potential to successfully backfill lighter pipelines and cables in weaker soils without problematic flotation occurring. This study is ongoing and is investigating the effects of backfill depth, pipe diameter, wider soil moisture content range and different soils types on the resistance to flotation and hopes to further improve design processes to avoid overly conservative flotation criteria.

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